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THEORIES OF THE ORIGIN OF RADIO SOURCES

E. M. BURBIDGE and G. R. BURBIDGE

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Paper Presented at

Symposium on Gravitational Collapse and Other Topics

in Relativistic Astrophysics, Dallas, Dec., 1963

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I. INTRODUCTION

The problem of the enormous energy required to explain the radio sources is not a new one - it has been with us since the time that:

1. Baade and Minkowski (1954) identified one of the strongest radio sources in the sky (Cygnus A) with a rather distant external galaxy; and
2. Dombrovsky (1954) and Oort and Walraven (1956) found the polarization predicted by Shklovsky (1953) in the optical radiation from the Crab Nebula radio source, thus verifying the theory that the emission was synchrotron radiation.

According to this theory, one can calculate the energy required in high-speed electrons and positrons and in magnetic field, for synchrotron radiation to be emitted at a rate given by the measured power output and frequency dependence of the radiation from sources at known distances. The calculations are well known (cf. Burbidge 1956a, b; 1959), and have recently been carried out with the newest observational data by Maltby, Matthews, and Moffet (1963).

The usual calculations assume that the energy is equally divided between that contained in the high-energy particles and the energy of the magnetic field, since this division gives the minimum energy requirements. Two sets of values are usually tabulated for the identified radio sources: one in which the minimum energy in field and in electrons and positrons (which are the radiating particles) is calculated, and one in which allowance is made for the presence of high-energy protons. The latter calculation is made because most suggested energy sources require, as the final stage in producing high-energy electrons, some kind of Fermi-type acceleration process and this would necessarily produce accelerated protons as well. Burbidge (1956a) and Ginzburg (1957) suggested that the electrons were secondary particles produced by interaction between the ambient gas and the accelerated protons; multiple production theory then gave the value of 100 as a reasonable estimate for the factor by which the proton energies exceed the electron energies needed to explain the emission.

This factor of 100 is customarily used in the more recent calculations. It has not been re-examined, and since the energy requirements are so enormous, even without this factor, we would like to draw the attention of theoretical workers to the need for a critical re-appraisal of the amount of energy which may be present in the proton flux.

The largest energy requirements discussed by Hoyle and Fowler at this conference are greater than the minimum energies for another reason. The radio sources in many cases lie well outside the galaxies in which they originate, and the regions where the radio emission is observed are the volumes which must contain the relevant magnetic fields. Magnetic fields of 10^{-4} or 10^{-5} gauss, which come from the calculations assuming equipartition, are much larger than can reasonably be expected to exist in intergalactic space. Thus the magnetic fields are almost certainly smaller than the equipartition values and the <u>total</u> energies consequently higher. We then arrive at the figure of approximately 10^{62} ergs, for the content of the most energetic radio sources. The possible consequences of the dominance of particle energies over magnetic field energies are interesting: the strong radio galaxies may contribute appreciably to the general cosmic-ray flux (Burbidge 1962a; Burbidge and Hoyle 1964; Burbidge 1964).

A good part of the following sections will be found in detail in a paper by Sandage and ourselves (Burbidge, Burbidge, and Sandage 1963).

II. VIOLENT EVENTS IN GALAXIES: RELATION BETWEEN STRONG RADIO SOURCES, QUASI-STELLAR RADIO SOURCES, AND SEYFERT GALAXIES

The galaxies that are strong radio emitters and the quasi-stellar radio sources can be related with another manifestation of short-lived energy release, taking place in the nuclei of Seyfert galaxies (Seyfert 1943). The latter have the following characteristics:

1. They have small, intensely bright nuclei (less than 25 pc in diameter in NGC 4151, for example, for which Sandage made a critical measurement, and which is shown in Figure 1).

2. The spectra of their nuclei show strong emission lines, sometimes of high excitation.

3. These emission lines are very broad, indicating, if this is Doppler broadening, velocities of 1000 - 3000 km/sec. The hydrogen lines are usually broader than lines of other elements.

The direct link with radio galaxies comes about because two galaxies are common to both categories: NGC 1068 (Figure 1) and NGC 1275 (Figure 2). The former is a relatively weak radio source, with only some 10^2 times the output from normal galaxies, but the latter is a strong source. Table 1 shows the total optical radiation emitted by some of these objects, and that emitted in the emission lines (mostly from the work of Seyfert), together with, for comparison, that emitted in optical radiation by M 82 (from the work of Lynds and Sandage 1963) and by the very strong radio source Cygnus A. It is likely that the Seyfert galaxies represent a milder manifestation of the same kind of violent event that must be postulated to explain the radio sources; possibly one may be witnessing an earlier stage in the event, or the event may be occurring in a different kind of galaxy.

The very large velocities indicated by the broad emission lines link the Seyfert galaxies to the quasi-stellar radio sources rather than to the ordinary radio galaxies. Schmidt (1963) noted that the widths of the identified spectral features in 3C273 were 50A; if this is Doppler broadening, it indicates a velocity range of ±1500 km/sec, which lies right in the range observed in Seyfert nuclei. In contrast to this, spectra of radio galaxies, other than those which are also Seyfert galaxies, do not have very broad lines. Indeed, Some have no emission lines at all, and the excitation is usually low. The excitation in the quasi-stellar radio sources also tends to be lower than in the Seyfert nuclei.

From high-energy resolution studies of NGC 1068, Walker (1963) has found that the nuclear region consists of separate cloud complexes moving about in a disordered fashion with relative velocities $\sim 10^3$ km/sec. This was earlier found to be the case in NGC 4151 by O. C. Wilson (unpublished). The large velocities in the Seyfert nuclei imply Mach numbers of 10 - 100; these will lead to a high rate of energy dissipation and heating. Further, these velocities exceed the escape velocity from the nuclear region and gas must be leaking out from it.

Estimates of the kinetic energy present in the nucleus can be made if the gas density can be calculated, as has been done by Woltjer (1959) (using Seyfert's photometry) in NGC 4151 and NGC 1068. Bearing in mind the uncertainties, we estimate the resulting kinetic energy to be $10^{55\pm2}$ ergs. It is interesting that this is of the same order as that estimated from the radio emission of NGC 1068 to be present in magnetic field and high-energy particles (4×10^{55} ergs if protons dominate; 3×10^{53} if only electrons are present). It is also of the same order of magnitude as the kinetic energy in the moving Hα filaments of M82 - 2×10^{55} ergs (Lynds and Sandage 1963).

Ten per cent of this kinetic energy of 10^{55} ergs, if dissipated in the disk of a galaxy such as NGC 1068, containing, say, 10^8 $M_{\odot}$ of gas, would be sufficient to impart motions of 50 km/sec. It is interesting that Walker (1963) has observed considerable anomalous velocities in the gas in the spiral arms of NGC 1068, whose velocities were analyzed by Burbidge, Burbidge, and Prendergast (1959) in terms of rotation of the galaxy.

There is one further connection between the Seyfert galaxies and the quasi-stellar radio sources that we would like to point out. It has been suggested that, at the distance of 3C 273, if there were a normal galaxy surrounding the bright star-like object, it should be visible on the existing photographs (the faint jet is plainly visible). If there is no such underlying galaxy, then the object must be different in kind from a radio galaxy such as NGC 5128. Now in many of the Seyfert galaxies, almost all the light is concentrated in the bright nucleus and the surrounding galaxy is much fainter than a normal galaxy (NGC 4151, NGC 7469, NGC 5548, and NGC 3516, shown in Figures 1, 3, and 4, are examples of this). This is not the case in all Seyfert galaxies; NGC 1068 (Figure 1) and NGC 3227 (Figure 4), for example, have outer parts of normal luminosity. We feel, however, that it may be a significant feature. It brings to mind many questions: are the Seyfert galaxies with faint outer parts and the quasi-stellar radio sources objects of low mass? low angular momentum and initial turbulent velocity? are they objects at an early evolutionary stage, about which a normal galaxy will later form? These are highly speculative questions which we cannot answer.

The lifetime for the energetic phenomena occurring in nuclei of Seyfert galaxies is about 2×10^4 years, from the time taken for gas moving with the observed velocities to escape from the observed nuclear dimensions. The time for the observed optical emission from the nuclei to exhaust the calculated store of kinetic energy is 2 orders of magnitude longer than this, i.e., $\sim 10^6$ years. The estimated frequency of Seyfert galaxies among normal galaxies then indicates that the Seyfert phenomenon is likely to be recurrent 100 times or more during the total lifetime of the galaxy. The estimated lifetimes for radio galaxies, as discussed earlier in this meeting, are thought to be $\sim 10^6 - 10^7$ years, while a time scale of $\sim 10^5$ years is indicated for 3C 273.

The evidence for linking the violent events in Seyfert galaxies, quasi-stellar radio sources, and the strong radio-emitting galaxies is reviewed in more detail in the paper already mentioned (Burbidge, Burbidge, and Sandage 1963).

III. POSSIBLE SOURCES OF ENERGY FOR RADIO GALAXIES

A variety of proposals have been made in the last decade to explain the energy for outbursts in galaxies of the magnitude required to explain the radio emission. Which energy source is responsible has considerable bearing on the types of particles ejected and also on the form of the particle energy spectrum. The possible energy sources can be considered in three groups. They are:

(a) Energy which is released by the interaction of a galaxy with material that was previously unconnected with it.

(b) Internal energy in a galaxy in the form of rotational energy, turbulent energy, or magnetic field energy which is released by some catastrophic process.

(c) Energy which is released in the evolution of stars. Included here is the gravitational energy released when stars are formed, the nuclear energy released in thermonuclear explosions, and rest-mass energy which is released if the star goes to a highly collapsed phase.

In category (a) the first proposal was that the energy was released in collisions between galaxies (Baade and Minkowski 1954). It is clear now that this argument cannot be sustained either on theoretical grounds or on the basis of the identifications of radio sources (cf. Burbidge 1961). In addition to the arguments given in that latter reference, the observational evidence now available shows that a large number of the sources of violent activity are centered on single galaxies, and the violence appears to start at their centers. NGC 1275 (see Figure 2) still presents an ambiguous situation in that it may be two systems in collision, but, as Minkowski has pointed out, the gas which has a velocity of 3000 km/sec relative to the main galaxy, if it is part of a colliding galaxy, should have a nucleus associated with it and there is no sign of such a nucleus. The large velocity difference might well be due to just such an outburst as that postulated in M 82, only of a more violent nature. We shall return to a consideration of the velocity field in NGC 1275 later.

A second proposal which falls into category (a) is that the energy is produced by the interaction of material in the galaxy with anti-particles or anti-matter and the subsequent annihilation. This was proposed by Burbidge (1956b) and Burbidge and Hoyle (1956). The general difficulty with this hypothesis is that one needs a mechanism for separating matter and anti-matter, whatever cosmology one is working with, and with anti-gravity ruled out by the arguments of Schiff (1959), this does not appear to be possible. The attraction of the hypothesis, at the time it was proposed, was that it provided electrons and positrons directly, without the need for the large flux of high-energy protons, and hence the energy requirements were reduced; although an acceleration process was needed, which would necessarily accelerate protons as well as electrons and positrons, at least the latter would be injected into this process at energies above the low energies where electron acceleration is relatively inefficient.

The most recent proposal in category (a) is that made by Shklovsky (1962) in which it is supposed that a galaxy interacts with material that has come from outside. He specifically considered the case of M 87, and argued that the material accreted by such a massive system falls into the center. Energy is released and material in the central region is accelerated outward in the form of plasma jets. While the rate at which material falls in is estimated by Shklovsky to be about 10 $M_\odot$/year, and this is compatible with the normal accretion rate for a galaxy of mass of the order of 10^{12} $M_\odot$ in a medium of density $\sim 10^{-29}$ gm/cm^3, the details of this process are not at all clear. In particular, it is not obvious how the acceleration occurs, or why infall of material should always give rise to a violent event which appears to emanate from the center. Thus we see that all of the proposals which fall into category (a) have difficulties associated with them.

We next turn to the processes involved in category (b). In its process of formation a proto-galaxy must dissipate energy both by radiation and by the generation of large-scale motions in the fragmentation which is required if stars are to form (cf. Hoyle 1953). It might be asked whether the violent release of energy in some systems is associated with this stage of evolution. The obvious objection to this is that the vast majority of systems in which violent events are taking place are well organized and often highly evolved galaxies, i.e., the elliptical galaxies. M 82 may be in a fairly early stage of evolution as deduced from the integrated spectral type of A5 and the large amount of uncondensed material, but it does not appear to be at the very early stage at which the dissipation of energy in this way is important. Of the peculiar systems catalogued by Vorontsov-Velyaminov (1959) and studied by us, and others, some are thought to be systems at an early stage of evolution; none of these have been identified with radio sources. A possible exception to this is NGC 4038-39, which is one of the weaker of the identified radio sources.

The question therefore arises as to whether any of the internal energy in a well-developed galaxy could be released suddenly to give rise to a violent event. The only proposal of this type which has been made is that by Hoyle (1961) who argued that in galaxies with considerable amounts of gas containing magnetic flux and large angular momenta galactic flares could arise through discharges following the winding up of the magnetic fields in the centers. This mechanism is similar to that proposed by Gold and Hoyle (1960) for the generation of solar flares. While the model proposed by Hoyle is not unattractive, it suffers from the disadvantage that the discharge conditions cannot be reached unless there is a large amount of gas already present in the galaxy, and also a large amount of angular momentum per unit mass. This means that massive systems with high rotations containing large amounts of uncondensed material are the obvious candidates to produce violent events. However, most of the galaxies in which violent events are seen do not fulfill all of these conditions. The elliptical galaxies which are massive, often contain little gas, and probably have little angular momentum. The Seyfert galaxies, while they do contain considerable amounts of gas and are fast rotating, do not appear to have sufficiently large masses or mass concentrations.

Finally, therefore, we come to the processes which are contained in category (c). Ginzburg (1961) has attempted to show that high-energy particles can be produced in the early stages of formation of a galaxy when gravitational energy is released. However, as we have described earlier it appears that none of the galaxies from which radio sources have emanated are systems which are recently formed.

As will be seen in what follows, energy release following star formation and evolution appears to give the best hope of explaining the phenomena. The observations of the Crab nebula and other supernova remnants in our Galaxy show that in, or following, stellar explosions the necessary conditions for a synchrotron source to appear are produced. Also, only in stellar explosions (novae and supernovae) are velocities generated of the magnitude seen in the Seyfert nuclei. Thus it is natural to suppose that the violent outbursts in galaxies are the result of multiple supernova outbursts or their equivalent in energy output.

Shklovsky (1960) argued simply that the supernova rate must have been very considerably enhanced so that some 10^6 or more supernovae have gone off at a rate of about 1 per year in an object like M 87. However, he had no argument as to why this should occur. Since supernovae only occur at the end of a star's evolution is is not reasonable to take this view unless it is supposed that the outbursts (a) are causally connected, or, (b) unless stars of very great mass are continuously being formed and evolve very rapidly. Cameron (1962) considered the rapid formation and evolution of massive stars in the nuclear region of elliptical galaxies. His calculations, however, neglected turbulent motions in the gas at the centers of such galaxies (Burbidge 1962b).

Burbidge (1961) proposed that a chain reaction of supernovae could be caused in the nucleus of a galaxy if one supernova went off naturally and the stellar density was sufficiently high so that other stars could be exploded. It was estimated that the star density required if such a mechanism were to work must be of the order of 10^6 - 10^7 stars/pc^3 and it was pointed out that there was no observational argument against this, particularly for the elliptical galaxies. Even higher star densities may be acceptable. The difficulty lies in understanding how a detonation wave can propagate even if sufficient light nuclei are present. This problem has not been solved, partly because the geometry involved is exceedingly difficult to handle. Also modern ideas concerning supernova outbursts suggest that an integral part of the normal supernova process is a catastrophic collapse. The chain reaction mechanism would not lead to this. Finally, if the magnitude of the energy released suggests that gravitational (rest-mass) energy is involved, this cannot be expected to occur by such a mechanism.

Since the theory of the release of gravitational energy by the formation, rapid evolution, and collapse of objects with masses as great at 10^8 $M_\odot$ has been fully discussed at this meeting by Hoyle and Fowler (see also Hoyle, Fowler, Burbidge, and Burbidge 1964), we shall not discuss this further here. We would like to mention one further possibility: that of a rapidly accelerating process of star collision leading to what might be called a "phase change" of matter in the nuclei of galaxies. Two independent investigations along these lines are underway at present: one by Gold at Cornell, and one by Ulam at Los Alamos. Since Gold will be talking about his work later during this meeting, we would just like briefly to discuss Ulam's ideas.

Of the radio galaxies which are close enough to be observed optically in detail, the strongest sources tend to be highly luminous, massive, mainly stellar systems, often with a characteristic extended luminosity distribution (cf. Matthews and Morgan, this conference). Figures 5 and 6 illustrate this. Figure 5 is an ultraviolet photograph of NGC 6166 (3C 338), in the cluster Abell 2199, taken with the Lick 120-inch telescope. Resolution in the radio observations is not sufficient to place the emission in any one component of this multiple elliptical, but the probability is that the optically unusual component - the brightest, very extended galaxy with the small ultraviolet nucleus - is responsible. Apart from the ultraviolet nucleus (which is mainly [O II] $\lambda 3727$ emission), the lack of central concentration of the light and the great outer extent, in comparison with other galaxies in the cluster, is to be noted. Minkowski has found a very large velocity dispersion of the stars in the nuclear region.

Figure 6 shows NGC 4782-3 (3C 278), photographed with the Lick 120-inch telescope. The difference in nuclear concentration in the two components of this double (already noted by Greenstein (1961) from the light distribution in his spectra), and the asymmetrical outer isophotes, are to be noted. There is no evidence for any appreciable amount of gas in this object; the outer isophotes must be due to asymmetrical stellar orbits.

Ulam is considering the motions in a small group of stars as a pilot problem in considering a bigger assembly. The question he asks first is: if a collision between two stars occurs, is a third star likely to collide in a shorter time than the time taken for the first two? Very probably this is the case. We do not know what the energy release in a stellar collision would be, but if a rapidly accelerating process of this type could lead to the agglomeration of the whole nuclear region, we should have a way of producing the $10^6 - 10^8\ M_\odot$ objects whose subsequent history might follow the course described by Hoyle and Fowler. Further, during such an agglomeration which would occur by energy exchange among stars, many stars would be thrown into orbits carrying them far from the nucleus, thus providing the greatly extended light distributions observed.

IV. CONCLUSION: THEORETICAL REQUIREMENTS

Let us collect together the observational facts that a successful theory of radio sources has to account for:

1. The most important is a means of obtaining the very large energies, already referred to many times during this conference.
2. The energy must be supplied in the right mode, i.e., in the form of high-energy particles and magnetic fields. In stressing the energy requirements, there is sometimes a tendency not to pay enough attention to this point. Although the magnetic energy may be already present in the form of galactic or intergalactic fields, there must be an efficient way of producing and accelerating high-energy electrons. For those radio sources which emit synchrotron radiation in optical frequencies, the lifetimes of the radiating electrons are no more than $10^2 - 10^3$ years so in general there must be a way of continuously supplying or reaccelerating these particles.
3. The lifetimes ($\sim 10^6$ years) of radio sources (and the shorter lifetimes of the explosive phenomena in Seyfert nuclei), together with the spatial frequency of these objects, show that the violent outbursts can be recurrent. Indeed, it is well known that in the Centaurus A source (NGC 5128), the radio

brightness distribution shows that the results of more than one outburst can be seen now. A satisfactory theory of radio sources must explain how recurrent outbursts can take place in any one galaxy. For example, if the formation, rapid evolution, and implosion of gas masses of $\sim 10^8 M_\odot$ are responsible, then we have to be able to do this more than once in a galaxy's lifetime. Similarly, if a "phase change" of matter in the center of a galaxy takes place, through rapidly accelerated stellar collisions and agglomeration, then this process has to be able to recur.

4. The theory has to account for the type of galaxy that is most likely to become a radio source, namely, spherical (low angular momentum), massive, mainly stellar systems with a somewhat unusual distribution of light and hence of stellar orbits. What is the relation of this to the lack of a galaxy of normal brightness around at least one of the quasi-stellar radio sources, and around the nuclei of some Seyfert galaxies?

5. The characteristic double radio sources have to be explained. What relation does this radio distribution bear to any axis of symmetry in the galaxy of origin - for example, the axis of rotation? Apparently, in one case there is a considerable component of velocity in the line of sight which could be interpreted as being due to rotation about an axis along the line joining the two sources (Schmidt, this conference). In NGC 5128, rotation of the gaseous system coexisting with the well known broad dust lane occurs about an axis perpendicular to the dust lane, i.e., about an axis which is inclined by 20° - 30° to the long axis of the main outer radio distribution (Burbidge and Burbidge 1959, Bolton and Clark 1960).

Turning from the radio distribution, that is, the distribution of high-energy particles, in typical radio galaxies, let us consider the distribution of more quiescent gaseous material ejected from a radio galaxy. We have two examples, M 82 and NGC 1275. Lynds and Sandage have deduced an outward velocity $\sim$ 1000 km/sec along the minor axis for the extensive filaments emitting Hα light in M 82. We have some spectra taken with the 82-inch telescope at the McDonald Observatory in several position angles, from which we hope to deduce the velocity field of the exploding gas in more detail. Dr. Vera Rubin is working on these plates at the moment, and she has brought to this meeting the results of measurements of one plate in position angle 83°, i.e., at $\sim 20^\circ$ to the major axis. It is interesting that the velocity gradient is greater than either Mayall's rotational velocity gradient along the major axis (Mayall 1960) or the explosive velocity gradient along the minor axis (Lynds and Sandage 1963); it is about 9 km/sec per second of arc.

In NGC 1275, we have obtained spectra in many position angles with the 120-inch telescope at Lick Observatory. We are working on these at present, in the hope of plotting out the velocity field in relation to the outer gaseous filaments which have a big velocity with respect to the central galaxy (+3000 km/sec in the line of sight (Minkowski 1957)). We find that there is ionized gas around the main galaxy, and the emission lines produced by this gas are inclined, giving the biggest velocity gradient in position angle 10° - 20°. It may be seen from Figure 2 that the extended outer filaments (where Minkowski found the big velocity displacement) are located north and west of the galaxy, mainly in position angle 110° - 120°, i.e., roughly perpendicular to the direction of our biggest velocity gradient. Our velocity gradients amount to a few hundred km/sec; we have found no run of velocities filling in the range from 5200 - 8200 km/sec nor any velocities showing a big negative displacement. If our measures indicate rotation of the galaxy, then the axis of rotation lies roughly in the direction of the big displaced velocity. This would support the concept of ejection along the axis of rotation, as in M 82.

6. Finally, we have to understand the role played by dust in radio sources.

The presence of dust in an otherwise normal-looking galaxy has come to be accepted as a good indication that a tentative identification with a radio source was in fact correct (M 84 (Wade 1960) is an example). The broad dust lane in NGC 5128 has already been referred to. The dust pattern in the radio source NGC 1316 (Fornax A) is another good case. It can be seen in Figure 7 that the dust has an unusual structure - rather like that in NGC 1275 - and extends close into the center but not through it (the dust lane seen in the shortest exposure in Figure 7 is slightly eccentric). A faint dark structure, possibly dust, was found in the brightest component of NGC 6166 (E. M. Burbidge 1962). Among the Seyfert galaxies, a curious dust bar near the center can be seen in NGC 3227 (Fig. 4). The very chaotic and remarkable dust structure in M 82 is one of its most striking features.

In conclusion, we have to emphasize that theory is still in an unsatisfactory state as regards accounting for the data described above. While we think there is a connection between Seyfert galaxies, on the one hand, and the radio galaxies and quasi-stellar radio sources on the other, we do not know to what extent the differences are differences in kind, in degree, or in time (i.e., stage of development of the aftermath of an explosion). The effect of recurrent outbursts may be to supply a considerable extragalactic component of cosmic radiation throughout space (Burbidge 1962a, 1964; Burbidge and Hoyle 1964). If gravitational collapse of massive objects occurs, there may be a considerable amount of "hidden mass" in existence in the universe. If outbursts have occurred in the past in present-day quiescent galaxies like our own, the effect of the degraded energy supply fed into kinetic energy and thermal motions on the generation of non-circular velocities and even on the renewal of spiral structure in galaxies are possibilities to be considered.

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Table 1

	Luminosity of Nucleus (erg/sec)	Energy Emitted in Emission Lines (erg/sec)
NGC 1068[a]	20×10^{42}	2.7×10^{42}
1275	19×10^{42}	
3516	25×10^{42}	1.2×10^{42}
4051	1×10^{42}	
4151	16×10^{42}	1.2×10^{42} (hydrogen wings)
		2.2×10^{42} (remainder)
7469	52×10^{42}	
M 82		2×10^{40} (Hα only)
Cygnus A	400×10^{42} (luminosity of whole optical system)	$\simeq 200 \times 10^{42}$

[a] New measure by A. R. Sandage

FIGURE CAPTIONS

Fig. 1 Two Seyfert galaxies, NGC 1068 (upper) and NGC 4151 (lower). Both photographed with McDonald 82-inch telescope on Eastman Kodak 103a - 0 emulsion, no filter. North at top, west at left in both; scale: 1 mm = 2".7 in both.

Fig. 2 Radio galaxy NGC 1275 (Lick 120-inch telescope; Eastman Kodak 103a - 0 emulsion, no filter). Main plate is 45^m exposure, showing outer filaments and dust structure; inset is 5^m exposure, showing structure in center. North at top, west at left; scale (same in both): 1 mm = 1".4.

Fig. 3 Upper: Spectrum of nucleus of Seyfert galaxy NGC 7469 (Lick 120-inch prime focus: 20^m exposure at a, 5^m exposure at b), showing very broad Hα and [N II] λ6583 emission, with narrow inclined cores. Lower: NGC 7469 and its companion (left) IC 5283 (Lick 120-inch telescope, Eastman Kodak 103a - 0 emulsion, no filter). North at left, east at top; scale: 1 mm = 1".5.

Fig. 4 Three Seyfert galaxies (all with McDonald 82-inch telescope, on baked Eastman Kodak IIa - 0 emulsion, no filter). Upper: NGC 3227 (with its elliptical companion NGC 3226); scale: 1 mm = 2".9. Lower left: NGC 3516, lower right: NGC 5548; scale for both: 1 mm = 2".6. North at left, east at top in all.

Fig. 5 Negative print of multiple elliptical radio source NGC 6166 (north at top, west at left). Photographed with 120-inch Lick telescope on baked Eastman Kodak IIa - 0 plate through Schott UG1 filter and Ross corrector (isolating small wavelength region around redshifted λ3727). Scale: 1 mm = 0".76. Note lack of central concentration and great outer extent of brightest component; also small UV nucleus (appearance of small cross about center is spurious, due to flaw in two-stage reproduction).

Fig. 6 Double elliptical radio source NGC 4782-3. Three exposures (45^m, 15^m, 5^m) with 120-inch Lick telescope on Eastman Kodak 103a - D emulsion through Schott GG11 filter. Note asymmetrical light distribution in longest exposure, and different light distribution in centers of two components. For all, north is at top, west at left; scale is 1 mm = 1".3.

Fig. 7 NGC 1316 (Fornax A radio source), showing dust structure. Exposures of 30^m (upper), 8^m (lower left), and 2^m (lower right), all at prime focus of 82-inch McDonald telescope on baked Eastman Kodak IIa - 0 emulsion, no filter. North at top, west at left; scale in all is 1 mm = 2".8.